NASA
SPACE VEHICLE
DESIGN CRITERIA
(ENVIRONMENT)

NASA SP-8037

ASSESSMENT AND CONTROL OF SPACECRAFT MAGNETIC FIELDS

SEPTEMBER 1970

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform design criteria for space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components will be issued as separate monographs as soon as they are completed. A list of all previously issued monographs in this series can be found on the last page of this publication.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the monographs will be used to develop requirements for specific projects and be cited as the applicable documents in mission studies, or in contracts for the design and development of space vehicle systems.

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September 1970

CONTENTS

1. INTRODUCTION 1

2. STATE OF THE ART 1
   - 2.1 Flight and Design Experience 2
   - 2.2 Sources of Magnetic Fields 5
   - 2.3 The Need for Spacecraft Magnetic Property Control 5
   - 2.4 Magnetic Property Control 6
     - 2.4.1 Pioneer Program 7
     - 2.4.2 Mariner Program 7
   - 2.5 Magnetic Measurements 8
     - 2.5.1 Sources 8
     - 2.5.2 Effect of Earth's Field on Measurements 9
   - 2.6 Magnetic Property Changes During Tests, Transport, and Launch Preparations 9
   - 2.7 Test Facilities 11

3. CRITERIA 13
   - 3.1 Assessment of Magnetic Field Problems 13
     - 3.1.1 Sensitive Equipment 13
     - 3.1.2 Sources of Magnetic Fields 13
   - 3.2 Magnetic Property Control 15

4. RECOMMENDED PRACTICES 15
   - 4.1 Sensitive Equipment 15
   - 4.2 Sources of Magnetic Fields 16
     - 4.2.1 Part Selection 16
     - 4.2.2 Part Arrangement and Compensation 17
     - 4.2.3 Wiring Techniques 17
   - 4.3 Testing 17

REFERENCES 19

APPENDIX A: Spacecraft Magnetic Fields and Magnetometer Characteristics 21

APPENDIX B: Glossary 23

APPENDIX C: Units and Conversion Factors 24

NASA SPACE VEHICLE DESIGN CRITERIA MONOGRAPHS NOW ISSUED 27

ASSESSMENT AND CONTROL OF SPACECRAFT MAGNETIC FIELDS

1. INTRODUCTION

The magnetic fields caused by sources aboard a spacecraft are of concern because of their effects on sensitive equipment and experiments. A mission objective common to many scientific spacecraft is the measurement of natural magnetic fields. The instruments used for these measurements will detect not only the ambient magnetic field but also the magnetic field of the spacecraft. Thus, the spacecraft magnetic field must be kept below a certain limit to prevent interference. This design criteria monograph provides guidance for assessment of magnetic effects and control of adverse effects in spacecraft design, development, and testing.

The degree of control depends on the mission objective. For instance, stringent requirements for stability of the spacecraft remanent magnetic field would be necessary when the mission involves measurement of the weak ambient fields of interplanetary space. For measurement of the strong fields near Earth and Jupiter, however, less rigid control requirements usually are acceptable. Control requirements could be severe, however, for near Earth spacecraft that measure small perturbations of the magnetic field or use magnetometers for attitude determination.

Experience has shown that the institution of magnetic restraints midway through a spacecraft program and attempts to clean up a magnetically dirty spacecraft are difficult and costly. Therefore, control procedures should be implemented early in the design program and continued throughout development, fabrication, testing of parts and subassemblies, final assembly, and prelaunch checkout of the spacecraft.

Magnetic fields from spacecraft sources also can create disturbance torques which affect attitude control systems. Criteria for the assessment of magnetic disturbance torques are contained in NASA SP-8018 (ref. 1).

Another design criteria monograph, NASA SP-8017 (ref. 2), describes the natural magnetic fields of the Earth, Moon, planets, and interplanetary space and gives models for design and mission planning.

2. STATE OF THE ART

The development of space vehicles to perform complex scientific missions, especially those involving investigations of magnetic fields, has brought about the need for constraints on the magnetic properties of the spacecraft to ensure that they do not interfere with the collection of data. As a result, magnetic property control programs have been developed which include criteria for parts and materials selection, test techniques, design considerations, and project management procedures. The requirements for magnetic property control (magnetic cleanliness) generally are expressed as a maximum allowable dipole moment of the spacecraft or as limits on the intensity and variability of the field at particular locations (e.g., instrument mounting sites) on the vehicle. The magnetic fields and magnetometer parameters for a number of spacecraft are listed in appendix A.

The terminology and systems of units commonly used in the field of magnetic property control and testing have evolved from the technical language developed in various specialized areas of science and technology dealing with magnetic phenomena. The terminology used in this monograph is that generally employed by magnetic property specialists. Selected definitions and comparisons of systems of units are presented in appendices B and C, respectively.

2.1 Flight and Design Experience

The Vanguard spacecraft provided an example of the adverse effect of a magnetic spacecraft part on sensitive instrumentation. A prelaunch check revealed that an attachment ring near the magnetometer was magnetic. The launch was delayed until a new ring could be fabricated and installed.

The magnetometer carried by the Dodge satellite is of the three-axis fluxgate type (ref. 3). It has a full scale range of ±250 gamma (γ) and was designed to achieve accuracy of a few gammas over the temperature and supply voltage ranges expected in the mission. The sensor was placed at the end of a mast to reduce the effects of magnetic fields associated with satellite hardware and currents. Operation of the magnetometer in orbit appeared to be very good, but careful observation of the data collected in many orbits showed unexpected results. When the satellite's attitude was stable as shown in figure 1, the magnetometer data indicated a periodic variation in total magnetic field with peak at satellite sunset (beginning of Sun occultation) and minimum at satellite sunrise (end of Sun occultation). This periodicity disappears when the satellite is tumbling as shown in figure 2. These observations suggest that the magnetometer is responding to a spurious bias generated by the spacecraft (ref. 3). Although not confirmed, the source of this bias may be the magnetic field built up by the solar array currents during solar exposure.

The need for control of magnetic properties was demonstrated on the first OSO spacecraft. Late in the program one of the photomultiplier tubes on the spacecraft was found to be highly magnetic. Its strong magnetic moment could have adversely affected the spacecraft's attitude control. Subsequently, a continuing effort was applied to control the sources of magnetic fields on all OSO spacecraft.

The use of extensible structures to displace sensitive instruments from major magnetic sources aboard a spacecraft is an effective measure for protecting those instruments from the remanent field. On the IMP-1 (Explorer 18) spacecraft, the magnetometers were located on booms far from the spacecraft because of the extreme sensitivity of the fluxgate and the rubidium vapor instruments (ref. 4). Figure 3 shows the locations of these sensors and their distance from the spacecraft's center. On Explorers 33 and 35, shown in figure 4, the sensors were mounted on one of the two booms approximately 2 meters from the spin axis to reduce the risk of interference from the spacecraft magnetic field (ref. 5). The lengths of the booms on Explorers 33 and 35 as well as on IMP-1 were constrained by configuration and reliability requirements and are the results of trade-offs between those requirements and the need to have the magnetometer distant from spacecraft magnetic sources.

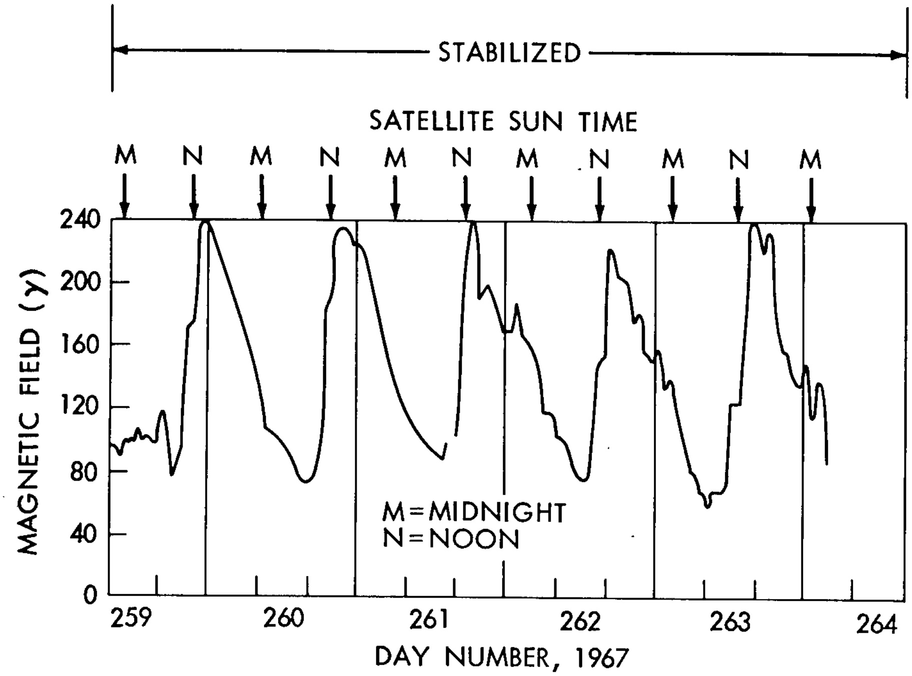

Figure 1. Magnetic field observed with Dodge satellite stabilized.

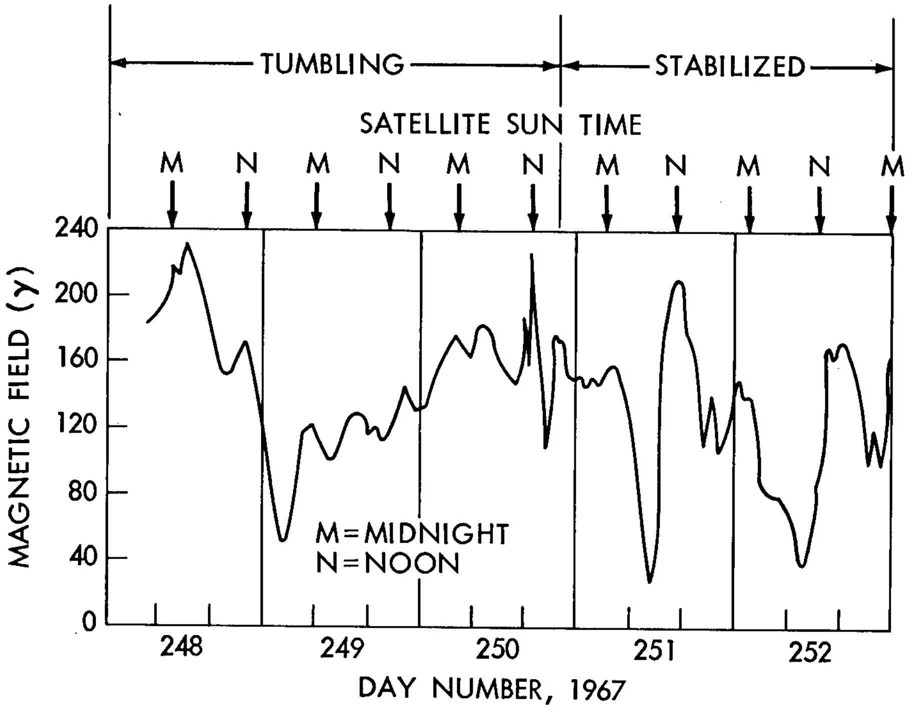

Figure 2. Magnetic field observed with Dodge satellite slowly tumbling and stabilized.

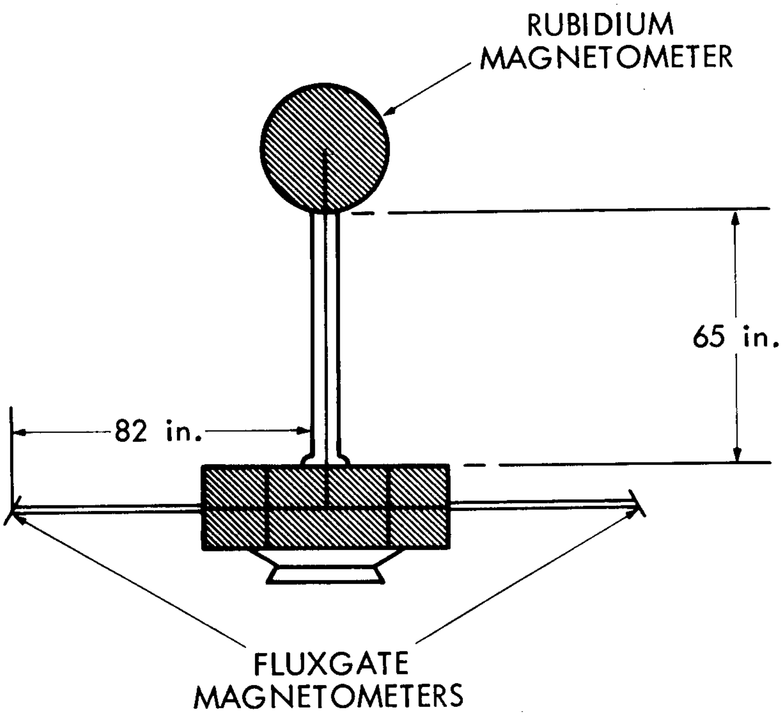

Figure 3. Fluxgate and rubidium magnetometers on IMP-1 (Explorer 18) spacecraft.

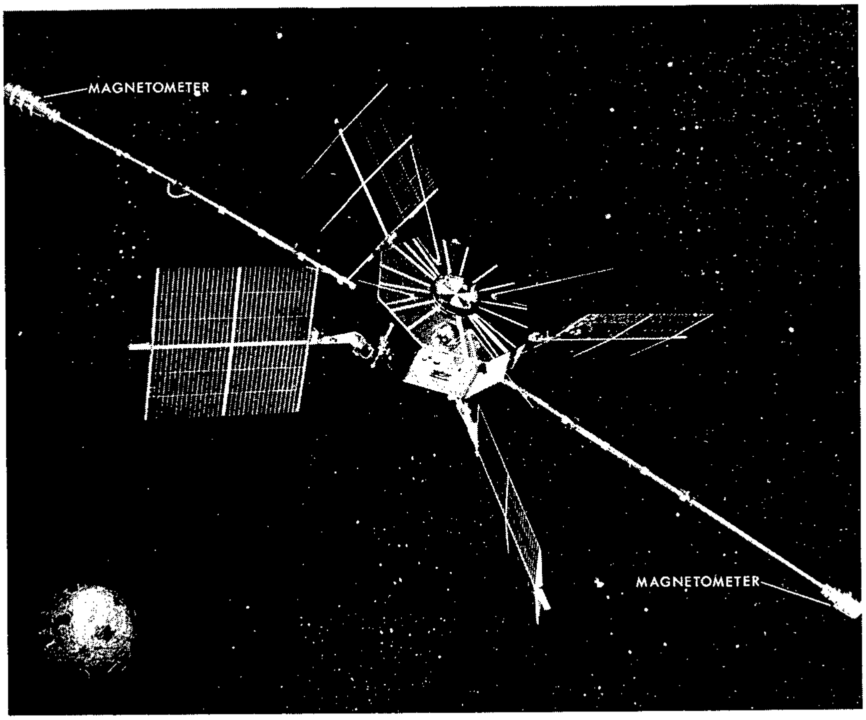

Figure 4. Magnetometers on Explorers 33 and 35.

In the case of the ISIS-1 spacecraft, tests indicated the presence of field disturbances at one of the magnetometer probes. It was caused by a steel ring in a nearby connector which was replaced by a nonmagnetic one (ref. 6).

On the ATS 4 and 5 spacecraft the magnetometer boom included an antenna which utilized ferrous wire and hardware. Because replacement of these magnetic items was not possible before launch, deperming was performed to reduce the field. Then mapping gave the needed parameters of the remanent field (ref. 7).

2.2 Sources of Magnetic Fields

There are three main sources of magnetic fields: "hard" magnets, "soft" magnetic materials, and current loops (ref. 8). The most common hard magnetic sources are permanent magnets which are used typically in such parts as latching relays, traveling wave tubes, tape recorders, ferrite isolators, and circulators. These devices individually may cause magnetic fields as high as 50000 γ at 1 foot.

The soft magnetic sources include all the common ferromagnetic materials and their alloys. These materials are subject to induced magnetic fields which are unstable in comparison to permanent magnets and may be difficult to predict and control. These fields are generally small compared with those caused by permanent magnets. Because of their widespread usage and magnetic instability, however, the soft magnetic materials often present the most difficult problems in spacecraft magnetic control.

There are current loops in the wiring harness between spacecraft parts, in the current paths in solar arrays, in solenoids and toroids, and in current routing inside assemblies. In addition, current loops can be produced by thermoelectric effects in structural members. The magnitude of the magnetic fields resulting from current loops is proportional to the current flow, the area enclosed by the loop, and the number of turns. Field intensity may be kept to a reasonably low level by proper selection of parts, part layout, and spacecraft harness wiring design.

2.3 The Need for Spacecraft Magnetic Property Control

Spacecraft carrying sensitive scientific instruments brought about the need for magnetic property control (magnetic cleanliness) programs. When accurate measurement of ambient magnetic fields is a primary objective of a spacecraft's mission, the magnetic requirements for the magnetometer sensor determine its mounting position. Instruments are presently available for spacecraft use which are capable of making measurements to an accuracy of better than 0.1 γ (ref. 9). For this accuracy the residual spacecraft magnetic field sensed by the instrument may have to be limited to a few gammas with fluctuations less than 0.1 γ.

Magnetic property control requirements may be quite severe for deep space probes such as the Pioneer spacecraft (fig. 5) which measure relatively weak ambient fields. The field intensity in interplanetary space is between 1 and 40 γ with an average value of about 6 γ near 1 AU (ref. 2). If the spacecraft magnetometers are to measure such fields, the spacecraft field must be kept low and stable.

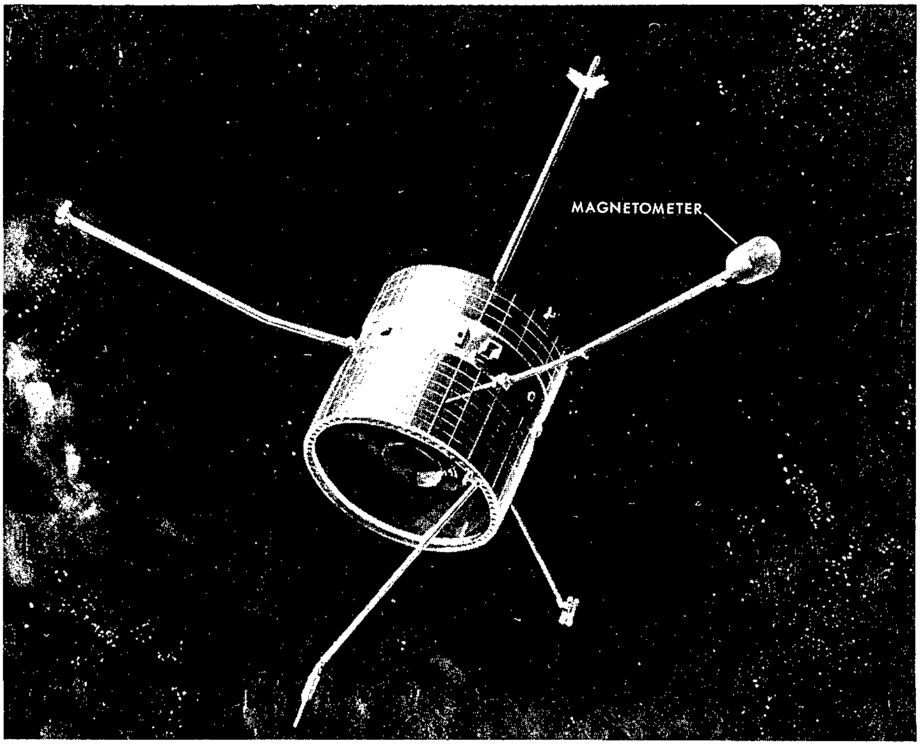

Figure 5. Magnetometer on Pioneer spacecraft.

Besides magnetometers, there are other sensitive instruments such as photomultipliers or electron beam devices that may be affected by a large spacecraft field and thus may require a comparable amount of control.

In the strong ambient fields near Earth (0.3 to 0.7 gauss at the surface) and Jupiter (5 gauss) (ref. 2) the torque on the spacecraft from a large magnetic moment can adversely affect the attitude control system. Methods of minimizing the satellite's magnetic moment as well as discussion of its effects on the spacecraft's attitude are presented in reference 1.

2.4 Magnetic Properties Control

Magnetic cleanliness is usually achieved by reducing the field at the particular locations on the spacecraft where sensitive instruments are mounted. The extent and level of detail of magnetic property control programs vary with mission requirements.

2.4.1 Pioneer Program

In the Pioneer Program, the control plan was elaborate enough to assure reduction of the field to 1 γ at 6 feet from the spacecraft center. All materials considered for use in the spacecraft structure were carefully evaluated before their inclusion in the Pioneer Approved Materials List (ref. 10). Nonferrous materials were used in the structure and mechanical hardware.

Electronic parts were magnetically screened before they were placed on the Pioneer Approved Parts List. Compensating magnets were effective in reducing the fields of permanent magnets in such parts as latching relays when use of these parts could not be avoided. Special fabrication techniques reduced the fields of diodes. Extensive studies were made to develop methods for minimizing the effects of the transformers, chokes, and inductors necessary for design of the power supply subsystem.

Detailed guidelines were established for limiting the stray field produced by currents within the spacecraft. These guidelines called for the following procedures: twisting leads carrying current greater than 10 mA with the return leads so that the stray field of the twisted pairs would be near zero, keeping the leads close to their returns in wiring through connectors to obtain some self-cancellation, twisting cabling in all power wiring throughout the spacecraft, and using extreme caution to avoid current loops in the grounding paths.

The effectiveness of magnetic control was monitored by the following tests and procedures (ref. 11).

- Functional test of spacecraft
- Spacecraft operating and failure mode test
- Spacecraft magnetic mapping
- Magnetization of spacecraft
- Spacecraft magnetic mapping
- Spacecraft appendage measurement
- Demagnetization of spacecraft
- Spacecraft magnetic mapping

2.4.2 Mariner Program

The magnetic control program of Mariner Venus 1967 spacecraft, shown in figure 6, was curtailed by severe hardware constraints as well as schedule and budgetary limitations (ref. 12). Because reduction of the spacecraft magnetic field was only partially successful, appropriate flight hardware was demagnetized to reduce the instability of the field.

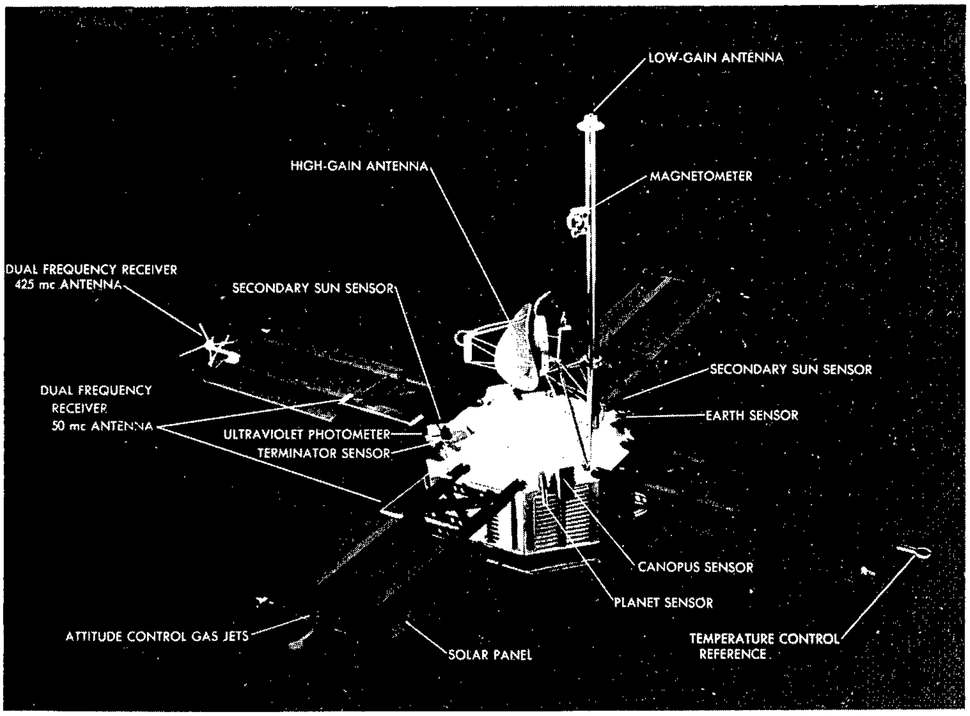

Figure 6. Magnetometer and other equipment on Mariner Venus 1967 spacecraft.

A few essential magnetic items carried over from the earlier Mariner Mars 1964 program, such as the motor driven power switch and the RF circulator switches, were shielded since their fields could not be reduced. The shields were made of Mu-metal or Moly-permalloy and effectively reduced the remanent field at the magnetometer. Magnetic mapping, magnetization, and demagnetization of the spacecraft subassemblies were carried out in portable magnetic test facilities at the Jet Propulsion Laboratory and at Cape Kennedy.

2.5 Magnetic Measurements

2.5.1 Sources

A series of measurements taken at one or more selected distances from a source of magnetic field is commonly used for estimating the contribution of that source to the magnetic field at the sensor. This procedure is frequently referred to as mapping the magnetic field of the source. The field contributed by a single source is frequently only a fraction of the total field permitted for the complete spacecraft, and therefore would have a magnitude below the threshold sensitivity of the magnetometers used for mapping the spacecraft. Hence, the measurements are taken at ranges closer to the source than the sensor aboard the spacecraft will be. Usually the measurements are made at a range of three to six times the largest linear dimension of the source (ref. 13). In taking these measurements, care is important in estimating the distance from the center of the magnetic mass of the source since an error in distance generally causes in proportion a three fold error in the field intensity results. Estimates of the contributed fields at the actual instrument location are made by using inverse cube rules for a dipolar source or spherical harmonic analysis for higher order multipolar sources. Reference 14 presents applicable spherical harmonic analyses.

Table I lists typical values for selected spacecraft parts in the preferred parts list being used at the Goddard Space Flight Center. The method used to obtain these values is presented in reference 15. Although most of the listed items utilize various ferrous and nonferrous materials, the special nonmagnetic items such as connectors illustrate the low field levels attainable when required.

The acceptance test of spacecraft assemblies includes (ref. 16)

- Mapping the remanent fields of the assembly before magnetic treatment
- Mapping after the assembly has been exposed to a dc exposure of 15 to 25 gauss
- Mapping after the assembly has been demagnetized
- Mapping the field produced by energized circuits in the assembly

2.5.2 Effect of Earth's Field on Measurements

Both the static value of the local geomagnetic field and its variations affect the measuring instruments when spacecraft magnetic fields are measured under normal field conditions on the Earth. Therefore, accurate measurement of the remanent fields usually is accomplished by placing the spacecraft in a low field magnetic coil facility where the geomagnetic field has been reduced. Biasing solenoids are used to remove the static value of the net uncompensated geomagnetic field from the output of the facility magnetometers.

A stable net field is a more difficult requirement than a reduced level of ambient field. When the desired accuracy of the spacecraft field measurements is of the order of 0.1 γ, the electrical stability and dimensions of the coil system are critical. Temperature changes of 0.1° K can change the coil output by 0.1 γ. Therefore, coil dimensions are controlled by stabilizing temperature with temperature compensation windings and maintenance of a constant current supply with regulation of 0.002 percent or better (ref. 16).

2.6 Magnetic Property Changes During Tests, Transport, and Launch Preparations

Upon completion of the perm-deperm series of tests, the spacecraft assemblies are subjected to environmental testing. Magnetic fields generated by vibration test equipment (shaker tables) and thermal-vacuum chambers may add to the remanent magnetic field of the spacecraft. Some of the larger shaker tables can produce nonuniform magnetic fields in excess of

TABLE I

TYPICAL MAGNETIC TEST DATA FOR SPACECRAFT PARTS

Item	Description	Field magnitude gamma (γ) at 12 inches		
		Initial perm	Post 15 gauss exposure	Post 50 gauss deperm
Capacitors	GL65CG 137D capacitor	8.2	20.9	.9
	0.047mfd, 100V ceramic	< .1	< .1	< .1
	7000pf ser.16, feed-thru	.1	.2	< .1
Connectors	DDM-50P-NMC 76	< .1	< .1	< .1
	UG-260 D/U	< .1	< .1	< .1
	75015-4425	< .1	< .1	< .1
Filters	1200-025	< .1	1.3	< .1
	1206-051	< .1	.3	< .1
Relays	T0-5 2PDT 420-1025	2.5	10.0	2.3
	Miniature 8210-1C-12	6.0	6.0	.5
	Crystal Can 2PDT,35Af1172	≤15.6	≤19.2	≤ .6
Transistors	2N 2060-2	.2	7.5	< .1
	2N 2849 (stud mount)	.4	.9	.1
	2N 2849 (T0-5)	.8	6.9	< .1
	2N 697	5.3	7.2	1.3
	2N 697 (3/8" leads)	2.1	3.0	.9
Microcircuits	Opp. amp. DP65A	3.0	5.0	<1.0
	MEM 5014 converter T0-116,40 lead	5.0	6.4	.6
	MEM 2009 multx, T0-86 14 lead	1.2	2.6	< .1
	T0-86 case, 3/4" leads	.2	5.2	< .1
	T0-86 case, 1/4" leads	< .1	1.8	< .1
Transformers	D0-T4	6.4	37.0	.2
	S0-4	.6	.6	.6
	MI-T 209	< .1	< .1	< .1
Diodes	IN3600 - 4AB	1.1	4.0	< .1
	IN3070 - 4AB	1.3	6.3	< .1
	IN645	< .1	< .1	< .1
	IN939B	.2	6.9	< .1
Resistors	RN 65D 1%	< .1	< .1	< .1
	NHG-50 1% (6921)	< 1.0	6.0	<1.0
	NH-50-14 3%	1.0	1.6	.1
Wires	RG 188 coax. PVF	< .1	< .1	< .1
	RG 178 Microdot (6 inches)	4.7	32.3	< .1
	44/0411-16, 18, 22, 26	< .1	< .1	< .1

30 gauss. Modern shaker tables usually have less intense fields but can still cause a change in remanent magnetic field. A small shaker table may have a 5 gauss field under equilibrium conditions and the field of a large shaker table may be as high as 20 gauss (refs. 4 and 17). A series of measurements taken after environmental testing indicates whether the remanent field has been affected. If a significant change is found, the deperm process is repeated.

In the period between the final spacecraft test and launch, accidental exposure to magnetizing fields may occur which, if undetected, may degrade the mission performance. Therefore, measurements of the spacecraft's field are desirable at the launch site but often are precluded by lack of facilities. If measurements show a significant change in the field, the deperm process is repeated.

The exposure history of a spacecraft during transport, handling, and launch preparation can be monitored by a passive device employing simple and effective magnetic flux recorders which was developed by E. Iufer at the Ames Research Center. Each of the flux recorders consists of three strips of Kovar arranged orthogonally and embedded in a plastic block. The recorders are depermed and then attached in several locations on the outer surfaces of the spacecraft. At any time before launch a recorder may be removed for examination for remanent field components on each of its axes. When more than one recorder is found to be magnetized in the same direction, the spacecraft is examined to determine if corrective treatment is needed.

2.7 Test Facilities

The development of a magnetically clean spacecraft requires the availability of magnetic test facilities that permit determination of the magnetic properties of the spacecraft and its component assemblies. The existing facilities fall into three categories: coil facilities, coilless facilities, and shielded rooms. The coil facilities employ coil systems which permit the establishment of a stable zero or low field within a fairly large volume. The coilless facilities provide, through proper site selection, a uniform ambient field. The shielded rooms are essentially walk-in magnetic shields which provide a fairly stable low field over a large volume.

Table II (updated from reference 18) lists the capabilities of some government owned coil facilities. Among the better known shielded rooms are those of the Socony Mobil Oil Company in Dallas, Texas, and of the Jet Propulsion Laboratory in Pasadena, California (refs. 19 and 20). Both shield developments employ Moly-permalloy sheets of high permeability and provide a field of a few gammas with small gradients.

TABLE II
CAPABILITIES OF MAGNETIC TEST FACILITIES

Characteristics	Goddard Space Flight Center Greenbelt, Maryland		Ames Research Center Mountain View, Calif.	TRW Systems Malibu, Calif. (Government owned)	Fredericksburg Magnetic Observatory Fredericksburg, Maryland	Naval Ship Research/Development Laboratory Annapolis, Maryland	Naval Ordnance Laboratory White Oak, Maryland
Nominal coil winding diameter, ft	42	22	12	20	17	40 x 40 x 50	30 x 30 x 40
Field intensity range capability, γ	0-120K	0-120K	0-100K	0.1-500K	1-130K	1-63K	1-100K
Uniform field, ft^3 (% variation)	110 (0.001%)	14 (0.001%)	24 (0.1%)	14 (0.01%)	14 (0.12%)	640 (0.05%)	900 (0.5%)
Compensation for diurnal variation	Auto.	Auto.	Auto.	No	Auto.	No	Auto.
Resolution (compensation accuracy), γ	0.1	0.1	0.1	0.1	0.5	1.0	0.25
Mapping of magnetic fields	Yes	Yes	Yes	Yes	No	Yes	Yes
Relative motion of the field	Yes	Yes	Yes	No	No	No	No
Thermal-vacuum conditioning	No	Yes	No	No	No	No	No
Rotation of test item	2-axis	1-axis	2-axis	1-axis	No	No	No

3. CRITERIA

The magnetic fields caused by sources aboard a spacecraft must be assessed during early design phases to determine whether sensitive equipment and experiments may be adversely affected by these fields. If field intensities indicate potential interference, a magnetic control program should be instituted.

Possible magnetic field problems should be evaluated by comparing the disturbance threshold of sensitive equipment with the magnetic field expected from the identified sources. Preliminary assessments may be made from data on comparable magnetic fields and sensitive equipment. However, refined assessments of the problem areas should use data developed through testing of the actual flight hardware during the spacecraft development program.

Guidelines for the assessment of spacecraft magnetic fields and establishment of a magnetics control plan are given below.

3.1 Assessment of Magnetic Field Problems

3.1.1 Sensitive Equipment

All instruments and other equipment which may be considered sensitive to interference of operation or other degradation of performance by exposure to magnetic fields should be identified. Such equipment includes but is not limited to

- Magnetometers
- Photomultipliers
- Image-dissector tubes
- Magnetic memory drums
- Low energy particle detectors
- Tape recorders

For each identified item, establish a threshold value of magnetic field which would adversely affect performance in the mission. The threshold values should be in terms of both the static and time-varying components of the disturbing field. Other features of the sensitive item that should be ascertained are the directional characteristics of its sensitivity, its planned location, and its orientation on the spacecraft.

3.1.2 Sources of Magnetic Fields

All components of the spacecraft containing permanent magnets or ferromagnetic materials should be identified. The parts to be considered in search of sources of permanent and induced magnetic field should include but should not be limited to

- Magnetic latching relays
- Traveling wave tubes

- Tape recorders
- Coaxial switches
- Transformers
- Inductors
- Solenoid valves
- Glass-to-metal hermetic seals
- Transistor cases
- Electronic component leads
- Fastener hardware (nuts, bolts, screws, and washers)
- Gears
- Bearings
- Motor (step, dc)

Electrical currents in conductors comprise the other class of magnetic field sources commonly found aboard spacecraft. Some of the sources of current-generated magnetic fields are

- Internal wiring of assemblies
- Windings of transformers and inductors
- Wiring harnesses
- Ground current paths in equipment
- Platforms
- Solar array conductors
- Solenoids
- Paths for currents caused by accidental thermocouples

3.2 Magnetic Property Control

When spacecraft magnetic fields present possible problems, a program to control magnetic properties should be instituted on the basis of priorities and constraints related to mission objectives. This program should

- Establish acceptable magnetic threshold levels for parts, assemblies, and spacecraft
- Exclude unnecessarily sensitive equipment in spacecraft design
- Avoid permanent magnets by alternate design approaches when possible
- Limit the use of soft magnetic materials
- Direct design of all current carrying and electrical grounding elements to minimize stray fields
- Include tests to accurately assess the magnetic properties of parts, assemblies, and the spacecraft

4. RECOMMENDED PRACTICES

If a magnetics control program is necessary, its management should be at the project office level. Support and authority should be given to magnetics control comparable to that given quality control, electromagnetic interference, or reliability programs. The magnetics control program should provide for the minimization of spacecraft magnetic field effects by careful consideration of the requirements for sensitive instrumentation, reduction or elimination of spacecraft magnetic sources, and frequent testing to check effectiveness of control measures.

4.1 Sensitive Equipment

Each piece of sensitive equipment should be identified, and its threshold of susceptibility to interference should be determined. In some cases alternate instruments that are less sensitive to magnetic fields can be used to meet the mission objectives without an elaborate and costly magnetics control program. However, if sensitive instruments such as the magnetometers used for measuring planetary or interplanetary magnetic fields have a high priority in a mission, then a stringent magnetic control program is essential. It is advisable to place all sensitive instruments as far as possible from the major onboard magnetic field sources. Such placements may require the use of extensible structures such as booms. The allowable length of these structures generally is limited by attitude, stability, reliability, weight, and structural requirements of the spacecraft.

4.2 Sources of Magnetic Fields

All parts which are potential sources of magnetic fields aboard a spacecraft should be identified. These parts then should be selected and arranged in their assemblies according to the methods which follow. By modification, these methods can achieve different degrees of magnetic cleanliness necessary for a particular spacecraft.

4.2.1 Part Selection

Whenever possible, a part with magnetic properties should be replaced by one made of nonmagnetic materials. Substitution of nonmagnetic mechanical fasteners is an example. The use of steel for such parts can be avoided entirely by using materials such as titanium, brass, and aluminum. Many materials commonly considered in industry to be nonmagnetic have been found to be magnetically unacceptable for spacecraft use (ref. 21). Table III lists some nonmagnetic metals normally suitable for spacecraft application. Similar tables listing nonmagnetic metals and alloys, their permeability, and maximum field magnitude at 2 inches are found in reference 15. Final selection of materials and alloys, however, should be based on a thorough magnetic testing program.

TABLE III

NONMAGNETIC METALS

Aluminum	Gold	Molybdenum	Silver
Antimony	Germanium	Niobium	Tantalum
Beryllium	Indium	Osmium	Tin
Bismuth	Iridium	Palladium	Titanium
Cadmium	Lead	Platinum	Tungsten
Chromium	Magnesium	Rhenium	Vanadium
Columbium	Manganese	Ruthenium	Zinc
Copper	Mercury	Silicon	Zirconium

Many transistors have nickel cases and leads which make them highly magnetic. It is recommended that a nonmagnetic nickel-silver alloy be used for the case material and the leads be clipped as short as possible (0.1 to 0.3 inches) before installation. In many cases, nonmagnetic parts can be obtained commercially. These parts are usually equivalent to parts already in use so no further qualification is needed. This is particularly true of resistors, capacitors, and several types of diodes.

The process of selecting suitable parts will not eliminate all magnetic sources from a spacecraft. Some vital parts depend on permanent magnets for proper operation. Other parts require high-permeability material, and a few devices make extensive use of ferrites and ferromagnetic materials.

4.2.2 Part Arrangement and Compensation

An arrangement of the magnetic parts within an assembly should be chosen so that the resultant field is minimized. When a number of identical parts with large permanent fields such as latching relays are used, they should be arranged so that the magnetic fields will cancel each other. When an assembly (such as a horizon scanner) contains several magnets, the magnets should be arranged to cancel or control the resultant field (ref. 9). In the case of traveling wave tubes, the field should be minimized by the attachment of small permanent magnets to the tube. Shielding (enclosing the disturbing part in a container of highly permeable material) can affect the functioning of the shielded part and the stability of its external field (ref. 19). Shielding generally should be avoided unless the resulting field reduction clearly outweighs such disadvantages.

4.2.3 Wiring Techniques

The magnetic field induced by currents usually can be avoided by careful wiring of the assemblies. It is almost impossible, however, to avoid leakage from transformers and inductors. The leakage can be reduced by employing toroidal transformers and inductors and by using extreme caution in the wiring of these parts. Magnetic fields caused by current loops of 10 mA or more within assemblies can be reduced by using leads of twisted pairs.

The wiring harness between assemblies and stray ground current paths in the structure should be minimized as sources of magnetic fields by careful design which limits the number and closed areas of loops and uses a single point grounding system in the spacecraft. Magnetic interference caused by currents flowing in solar cell arrays should be controlled by a backwiring technique in which the current return wires are routed directly behind the solar cells and thus tend to cancel the effects of the outgoing current. Another advantage of this technique is that if part of the array is lost, the magnetic field will not change significantly.

4.3 Testing

Testing throughout the magnetic control program is essential. To assure use of clean parts, test procedures should be established for magnetic screening of all parts at the time of incoming inspection. Upper limits for the permissible field should be established during the parts qualification program, and those parts whose field is found to be above the specified maximum should be rejected for spacecraft use. Testing is carried out after the parts are magnetized in a 15 to 25 gauss field. Measurements of the parts should be taken at distances 3 to 6 times the largest linear dimension of the part. The contributed fields at the actual location of the part on the spacecraft should then be obtained by inverse cube rules for dipolar sources and by spherical harmonic analysis for multipolar sources (ref. 14).

Assemblies should be tested individually as part of qualification and acceptance tests. The tests should include measurements of the induced, stray, and permanent magnetic fields of the assembly before and after exposure to a 15 to 25 gauss field. Testing after demagnetization indicates the change which might occur in the assembly magnetic field during testing and launch. The demagnetizing fields should be at least as large as the greatest previous exposure in order to properly remove remanent fields (ref. 17).

After part and assembly testing, the assembled spacecraft should be tested. It is recommended that spacecraft testing be performed in a controlled low field (if facilities are available) or a stable ambient environment and should include the measurement of the dc magnetic fields of the nonoperating spacecraft and of the stray fields associated with all operating modes of the spacecraft. Mapping of the dc magnetic fields is accomplished through measurements taken at specified distances along the radial from the spacecraft's center during rotation of the spacecraft about a set of three mutually orthogonal axes. The stray field of solar arrays should be measured separately when it is difficult to illuminate the arrays during the spacecraft testing. The solar array testing should include measurements of the stray fields associated with normal operation of the solar array and with operation in failure modes in which various single strings of solar cells are nonoperative. Further details on spacecraft testing techniques, facilities, and instrumentation are provided in references 4, 6, 8, 10, 12, 17, and 22.

The above tests for the spacecraft and the solar cell arrays should be performed before and after magnetization and demagnetization. Test facilities that provide a stable magnetic field of low intensity which is uniform over a fairly large volume are helpful because the permanent and induced effects can be separated readily.

After the post deperm test of the spacecraft, consideration should be given to the use of flux recorders to monitor possible accidental exposure to magnetizing fields during transport, handling, and launch preparations. If flux recorders are not used, prelaunch measurement of the spacecraft's field should be made at the launch site. If exposure is indicated by the flux recorders or the prelaunch measurement, corrective measures, such as a deperm process, should be undertaken.

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APPENDIX A

Spacecraft Magnetic Fields and Magnetometer Characteristics

Spacecraft	Launch date	Weight (lb)	Magnetometer type	Maximum spacecraft field disturbance (γ) at magnetometer	Magnetometer characteristics	
					Range (γ)	Sensitivity (γ)
Pioneer 5	3/11/60	95	Induction coil	—	$<10^3$	0.05-5.0
Explorer 10	3/25/61	79	Rubidium Fluxgate	$<$ 1.0 $<$ 1.0	30-5000 ±50	3.0 0.3
Explorer 12 (S-3)	8/15/61	83	Fluxgate	11.0	±500	10.0
Explorer 34 (S-3a)	10/2/62	89	Fluxgate	$\leq$ 4.0	±250	5.0
Explorer 15 (S-3b)	10/27/62	98	Fluxgate	$\leq$ 3.0	±4000	40.0
Alouette	9/29/62	320	Fluxgate	$\leq$710.0	60000	±18.0
Explorer 18 (IMP-1)	11/27/63	138	Rubidium Fluxgate	$<$ 1.0 $<$ 0.6	$<$300 ±40	±0.25 ±0.25
OGO-1	9/4/64	1073	Rubidium Fluxgate	$\leq$ 1.5 $\leq$ 3.8	3-14000 ±500	±3.0 ±3.0
Explorer 21 (IMP-2)	10/4/64	136	Rubidium Fluxgate	$<$ 1.0 $<$ 0.6	$<$300 ±4.0	±0.25 ±0.25
Explorer 26 (EPE-4)	12/21/64	101	Fluxgate	$<$ 1.0	$<2x10^3$	±2.0
Explorer 28 (IMP-3)	5/29/65	130	Rubidium Fluxgate	$<$ 1.0 $<$ 0.6	$<$300 $<$40	±0.25 ±0.25
Mariner 4	11/28/64	575	Helium	$\leq$ 35.0	±360	±0.35
OGO-2	10/14/65	1118	Rubidium Fluxgate	$<$ 0.5 $<$ 1.3	13000-64000 ±500	±2.0 ±0.25
Pioneer 6	12/16/65	140	Fluxgate	$\leq$ 0.25	±40	±0.25

APPENDIX A (Continued)

Spacecraft	Launch date	Weight (lb)	Magnetometer type	Maximum spacecraft field disturbance (γ) at magnetometer	Magnetometer characteristics	
					Range (γ)	Sensitivity (γ)
OGO-3	6/6/66	1135	Rubidium Fluxgate	< 0.6 < 1.6	3-14000 ±500	±0.25 ±0.25
Explorer 33 (IMP-4)	7/1/66	206	Fluxgate	< 0.25	±40	±0.25
Pioneer 7	8/17/66	140	Fluxgate	≤ 0.25	±40	±0.2
ATS-1	12/6/66	660	Fluxgate	≤100.0	+925 to -625	1.0
Explorer 34	4/24/67	163	Fluxgate	< 0.3	±40	±0.25
Mariner 5	6/14/67	540	Helium	≤ 7.1	±360	±0.35
Explorer 35 (IMP-5)	7/19/67	230	Fluxgate	< 0.2	±40	±0.25
OGO-4	7/28/67	1240	Rubidium Fluxgate	< 0.4 < 1.0	13000-64000 ±500	±2.0 ±0.25
Pioneer 8	12/13/67	145	Fluxgate	≤ 0.25	±40	±0.2
OGO-5	3/4/68	1347	Rubidium Fluxgate	< 1.5 < 2.2	3-14000 ±500	±2.0 ±0.25
Explorer 38 (RAE-1)	7/14/68	417	Fluxgate	< 32.0*	±10000	±100.0
ATS-4	8/10/68	864	Fluxgate	≤ 32.0*	±500	±0.25
Pioneer 9	11/8/68	148	Fluxgate	≤ 0.25	±40	±0.2
ISIS-1	1/30/69	532	Fluxgate	<600.0*	±60000	±40.0
OGO-6	6/5/69	1393	Rubidium Fluxgate	≤ 0.2 ≤ 0.5	13000-64000 ±500	+0.25 +0.25
ATS-5	8/12/69	750	Fluxgate	≤116.0*	±500	±0.25
Explorer 41 (IMP-7)	6/21/69	157	Fluxgate	< 0.5	±40	±0.25

* Spacecraft compensated with permanent magnets

APPENDIX B
Glossary

Coil system - A set of conductors arranged to produce a magnetic field along one or more axes when electrically energized. Normally, such coil systems are used to neutralize the Earth's magnetic field over a limited volume and are arranged in orthogonal triaxial fashion.

Current loop compensation - The compensation of a field or moment by the installation of a current loop to produce an opposing field or moment, also called degaussing.

Deperm - To demagnetize an object by exposing it to an alternating magnetic field which diminishes to zero.

Expose - Same as Perm (verb).

Gauss - Same as Perm (verb); also a unit of magnetic field intensity (appendix C).

Induced moment - Also called induced magnetization, that moment which exists in a ferrous object only as long as it is in the presence of a field (reduces to zero when the field is removed).

Perm (noun) - Contraction of "permanent magnetization;" the remanent magnetization evident after removal of an applied field.

Perm (verb) - To magnetize an object by exposure to a magnetic field.

Remanence - Value of the flux density when the applied field is decreased to zero.

Remanent field - Permanent magnetization, the field remaining after removal of an applied field.

Stray field - Magnetic field resulting from flow of current.

Stray field test - The actuation of each onboard circuit so that magnitudes of stray magnetic fields may be determined.

Torquemeter - An instrument for measuring the torque produced by interaction of a magnetic field and the dipole moment of a spacecraft or subsystem.

APPENDIX C
Units and Conversion Factors

Several systems of units have been commonly used to describe the characteristics of magnetic fields. The system of electrostatic units (esu) uses Coulomb's law; and the system of electromagnetic units (emu) uses the law of attraction between currents. The Gaussian system expresses magnetic quantities in emu and electric quantities in esu. In the Gaussian system, the magnetic flux density (B) and the magnetic field intensity (H) are used interchangeably. (This is so because in the relationship, $B = \mu H$, the permeability, μ, is unity for a vacuum, making B and H numerically equal for vacuum conditions.) Confusion can result when it is necessary to distinguish between the magnetic quantities represented by B and H.* Another unit used for B is the gamma (γ) which was first introduced in studies of geomagnetism. When μ is unity, gamma equals 10^{-5} gauss and is often used for both field intensity and flux density (ref. 23). In 1960, the Eleventh General Conference on Weights and Measures adopted the International System of Units (SI), based on the meter, kilogram, second, ampere, kelvin, and candela. In SI units, the tesla (T) is the unit of magnetic flux density, B, and the ampere per meter (A/m) is the unit of magnetic field strength, H (ref. 24).

Units used in this monograph are of the emu system. Relationships between SI units and emu and esu are given in tables C-1 and C-2 for the magnetic flux density and magnetic dipole moment (ref. 24).

TABLE C - 1

Magnetic Flux Density

System of units	equals* one	T	Γ	γ
SI	webers/meter^2 (Wb/m^2) or tesla (T)	1	10^4	10^9
emu	gauss (Γ)	10^{-4}	1	10^5
**	gamma (γ)	10^{-9}***	10^{-5}	1

*Equivalent in free space, i.e., permeability, μ, equals one.
** Not part of a system.
*** 1 nanotesla (nT).

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*Iufer, E. J., "Magnetic Field Sensors," NASA Ames Research Center, 1970 (to be published in ISA compendium).

APPENDIX C (Continued)

TABLE C - 2

Magnetic Dipole Moment ($\vec{\mu}$)

System of units	equals* one	Loop (A-m^2)	Dipole (Wb-m)	Loop (pole-cm)	Dipole (pole-cm)
SI	ampere-meter^2 (A-m^2)	1	4π x 10^{-7}	10^3	10^3
	weber-meter (Wb-m)	$\frac{10^7}{4\pi}$	1	$\frac{10^{10}}{4\pi}$	$\frac{10^{10}}{4\pi}$
emu	pole - centimeter (pole - cm or upc)	10^{-3}	4π x 10^{-10}	1	1

*Equivalent in free space, i.e., permeability, μ, equals one.

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NASA-Langley, 1970 —— 31